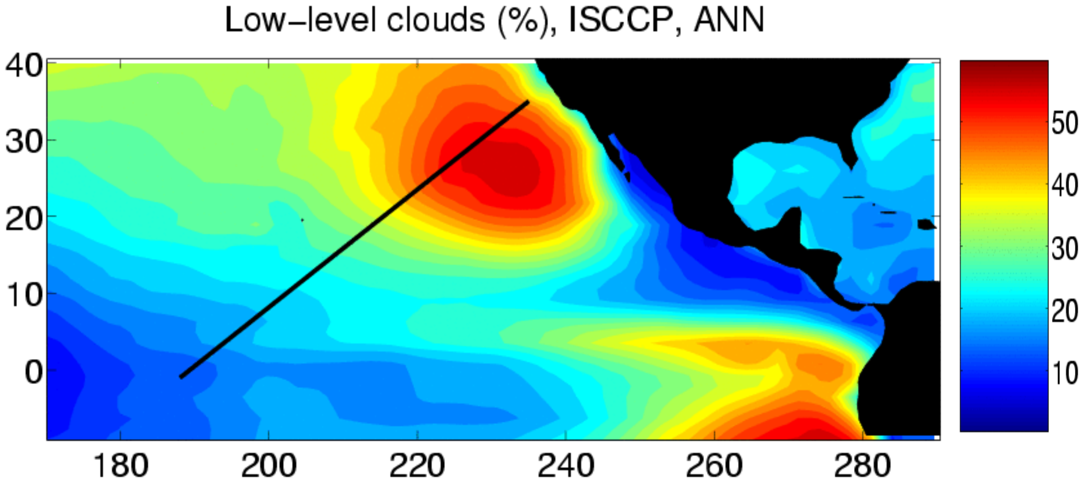
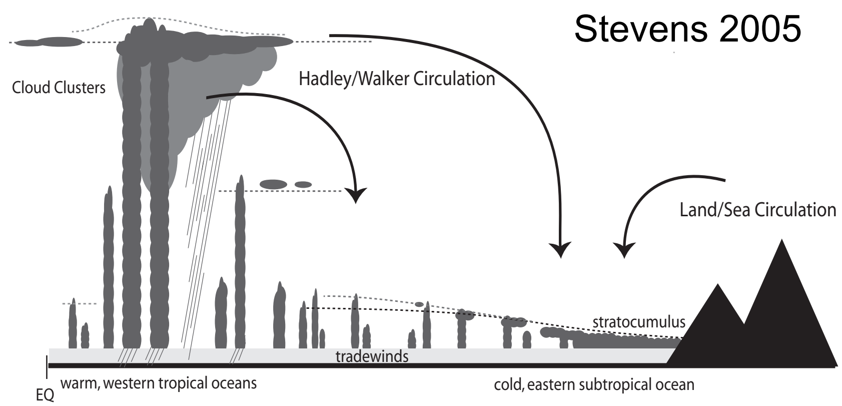
Stratocumulus to Cumulus Transition CPT

Chris Bretherton (UW) and Joao Teixeira (JPL)

Goal: Improve the representation of the cloudy boundary layer in NCEP GFS and NCAR CAM5 with a focus on the subtropical stratocumulus to cumulus (Sc-Cu) transition





NCEP H. Pan (PI), J. Han, R. Sun
NCAR S. Park (PI), C. Hannay
JPL J. Teixeira (CPT lead PI), M. Witek
U. Washington C. Bretherton (PI), J. Fletcher, P. Blossey
UCLA R. Mechoso (PI), H. Xiao
LLNL S. Klein (PI), P. Caldwell

NOAA funded
Aug. 2010 - 2013
(additional internal JPL and DOE funds)

Motivations for CPT

NCEP

- Vision: contribute to PBL and cloud physics development for a NOAA weather-seasonal-climate operational model

- Diagnose and improve clouds in operational GFS
- Evaluate free-running coupled GFS with climate model metrics
- Use single-column GFS as testbed for new parameterizations

NCAR

- CESM/CAM5 has new moist physics & aerosol
- Their interaction is inadequately understood and suboptimal

CPT Current Main Tasks

a) Better coupled/uncoupled climate diagnostics for GFS

b) Study PBL cases with GFS SCM and LES models

c) Evaluate physics modifications in short coupled GFS runs

d) Development/testing of PDF cloud scheme in NCAR

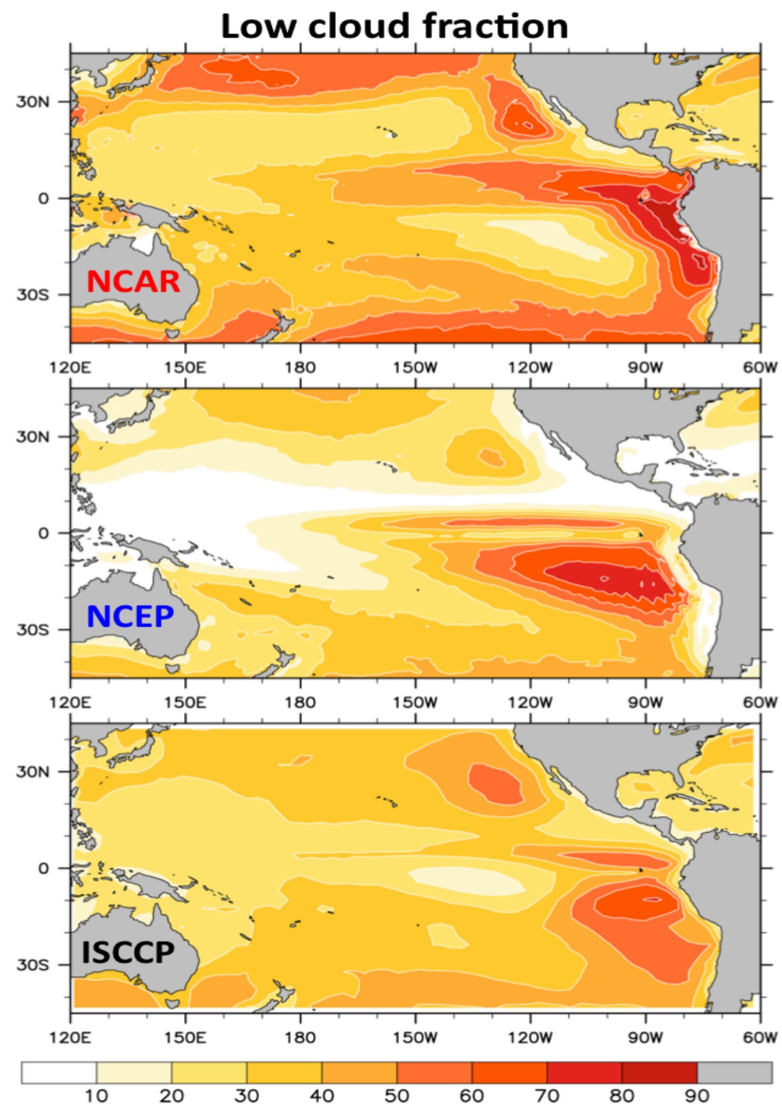
e) Development/testing of EDMF parameterization in NCEP

$$\overline{w'\varphi'} = -k\frac{\partial \overline{\varphi}}{\partial z} + M(\varphi_u - \overline{\varphi})$$

Siebesma & Teixeira, 2000

NCEP Model Diagnostics

- NCAR CESM 1.0 (coupled version of CAM 5.0, 200-year run)
- NCEP CFS (coupled version of operational GFS, 50-year)
- Modified NCAR AMWG diagnostic package to add NCEP GFS output
- NCEP has TOA energy imbalance
- Both models reproduce global circulation patterns
- Both models have cloud biases



Xiao et al, UCLA

50 yr C-GFS vs. 100 yr CESM: AMWG metrics

cor coef: Space-Time	b40_20th_c02c_76jpl	NCEP_GFS
	ANN	ANN
Sea Level Pressure (ERA40)	0.959	0.956
SW Cloud Forcing (CERES2)	0.714	0.408
LW Cloud Forcing (CERES2)	0.769	0.781
Land Rainfall (30N-30S, GPCP)	0.811	0.751
Ocean Rainfall (30N-30S, GPCP)	0.757	0.733
Land 2-m Temperature (Willmott)	0.876	0.911
Pacific Surface Stress (5N-5S,ERS)	0.797	0.834
Zonal Wind (300mb, ERA40)	0.960	0.957
Relative Humidity (ERA40)	0.874	0.906
Temperature (ERA40)	0.932	0.984

C-GFS pattern correlations better than CESM1 for:

- Pacific surface stress
- Land surface temperature
- 3D T and RH

C-GFS climatology is remarkably good for a weather-tuned model

GFS Problem Area 1: Global energy budget

[W m^{-2}]	GFS	CFS	NCAR	CERES2
TOA F_{net}	9.0	7.4	-0.2	0
TOA-surf ΔF_{net}	4.3	4.4	0.0	
TOA SW_{net}	259	253	238	240
TOA SW_{clr}	284	285	287	287
SWCRF	-25	-32	-49	-47
TOA LW_{net}	250	246	238	240
TOA LW_{clr}	268	265	260	269
LWCRF	18	19	22	30

Two large compensating biases in GFS (and in CFS):

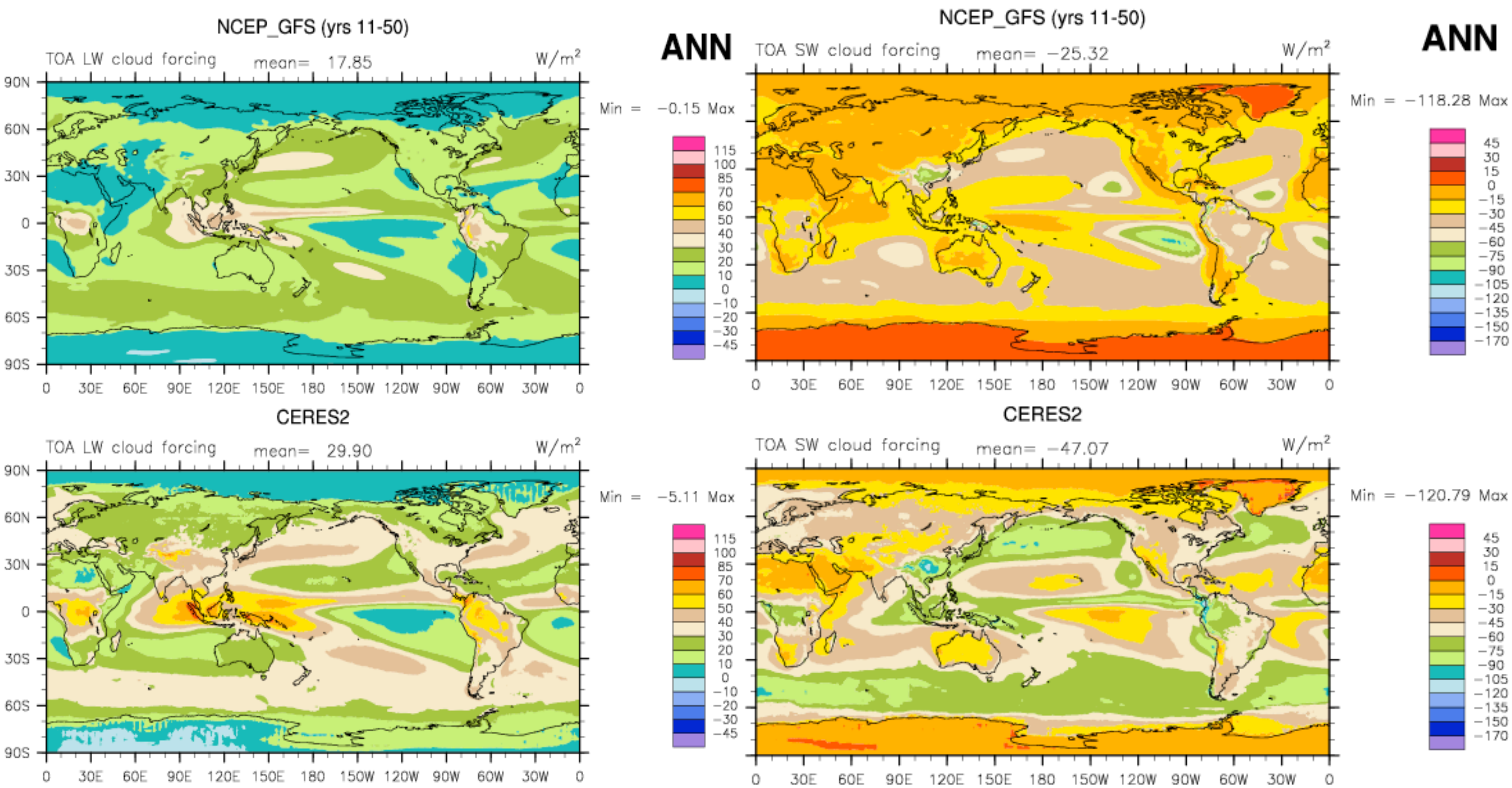
- Net spurious energy loss in atmosphere [and ocean?]
- SW, LW CRF 40-50% too low → 10 W m^{-2} too much net rad

GFS problem area 2

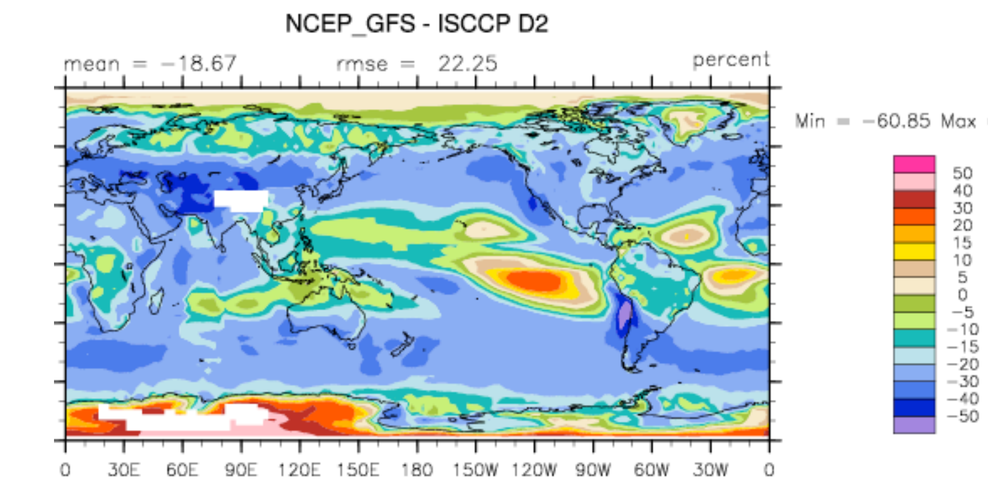
Large low bias in GFS cloud radiative forcing:

Regions of deep high cloud

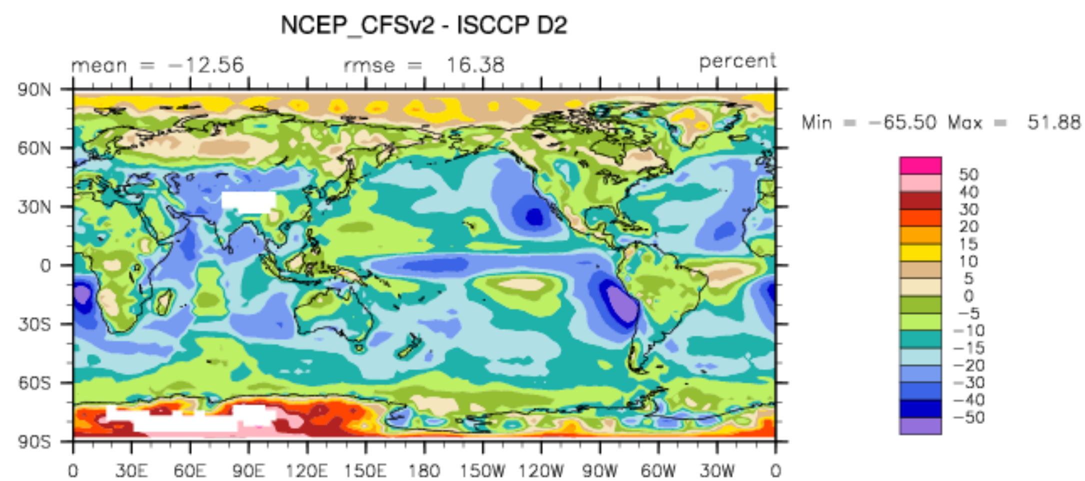
Subtrop. Sc too far offshore



Main culprit: Too little cloud cover in GFS

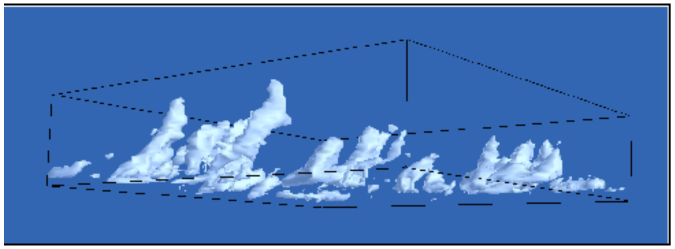


….BUT also in CFS



Cloud Parameterization? Microphysics? Vertical mixing?

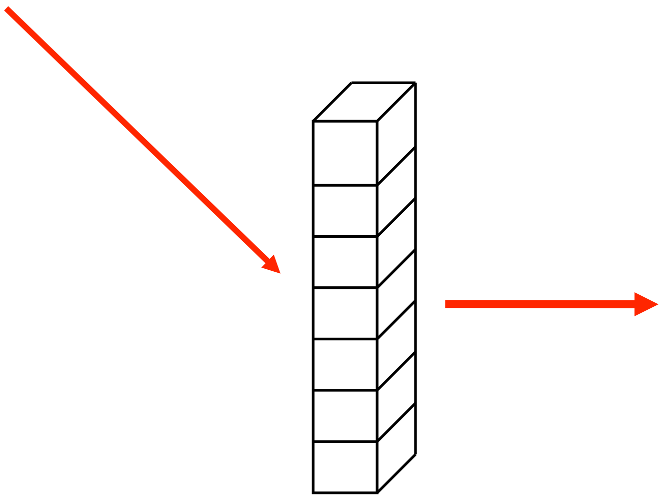
Single-column testing and improvement of GFS

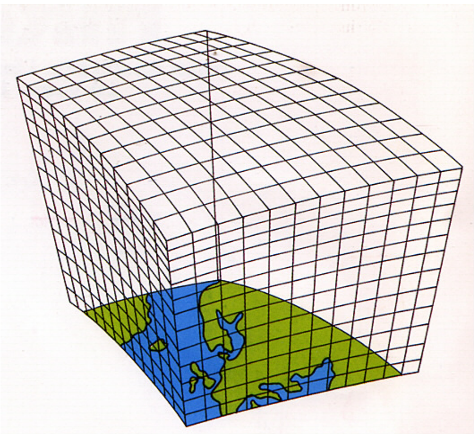


High-resolution model data:

Large Eddy Simulation (LES) models

Cloud Resolving Models (CRMs)





Testing in Single Column Models:

Versions of Climate Models

3D Climate/Weather Models:

Evaluation and Diagnostics with satellite observations

LES/CRM models provide unique information on small-scale statistics

Single-Column Modeling with GFS
(Fletcher et al.)

- GFS SCM developed by UW and NCEP with recent physics
- SCM has been adapted to several GCSS cases (Sc, shallow Cu, Sc-Cu transition) for which LES and observations exist
- SCM used at JPL to implement EDMF scheme in GFS

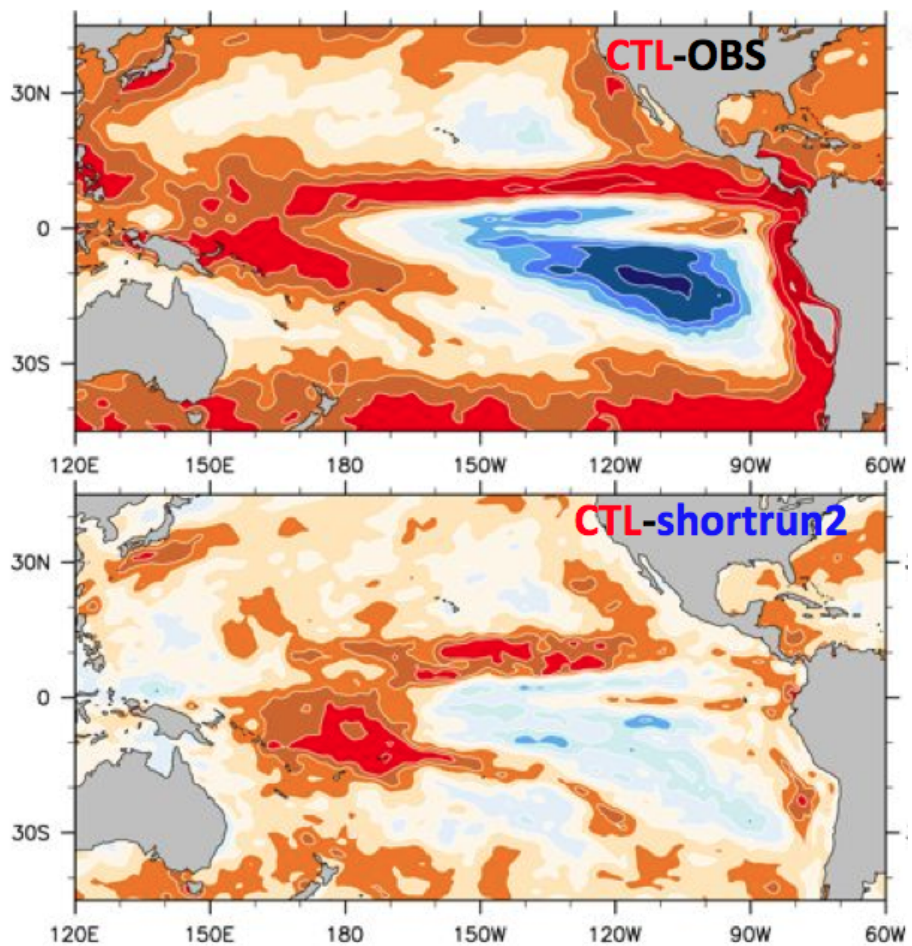
LES/SCM study of BOMEX Cu case:

- Too much rain
- Cloud cover problematic
- Physics changes from LES:
  increase lateral entrainment 3x
  decrease precip efficiency 2x

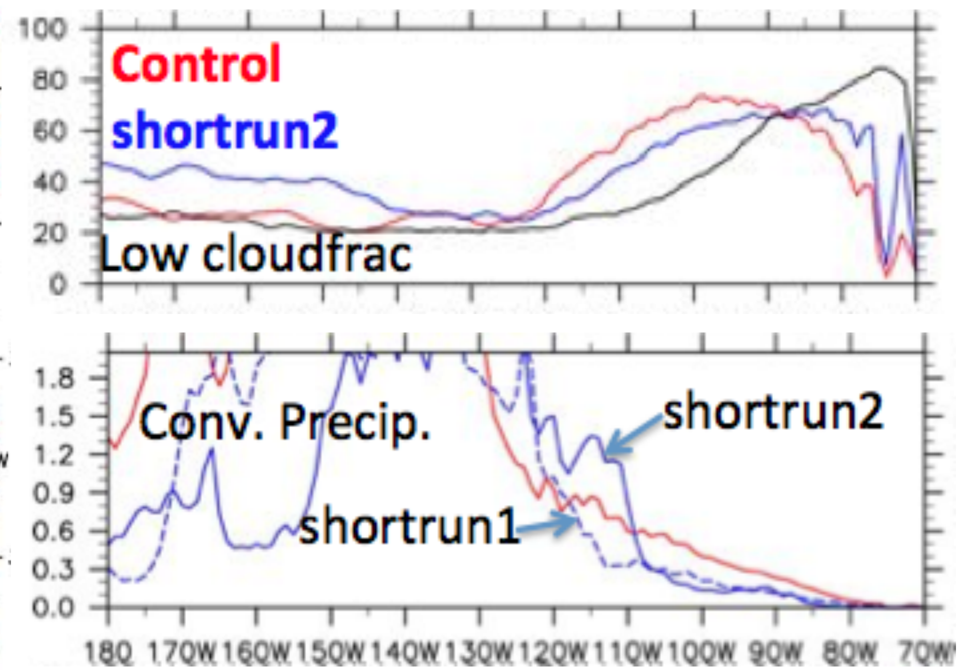
Sensitivity to Shallow Cu changes (shortrun2)

SON Year 1

ΔSWCRF



20S x-sections



- ✓ Increase in trade Cu cloud
- ✓ Decrease in ShCu rain
- ✓ Shift of Sc toward coast
- ✓ SWCF improvement

Energy loss and TKE dissipation heating
(Han et al.)

$$\varepsilon = \underbrace{-K_h \frac{g}{\theta_v} \frac{d\theta_v}{dz}}_{\text{buoyancy production}} + \underbrace{K_m \left| \frac{d\mathbf{u}}{dz} \right|^2}_{\text{shear production}}$$

EXP (total and low cloud fraction [first 4 month averaged])	TOA (W/m^2)	SFC (W/m^2)	Difference (W/m^2)
CTL (49.7%: 28.5%)	9.9	5.3	4.6
EXP3 (55.4%: 35.8%)	1.5	0.8	0.7

EXP3: TKE dissipation heating + cloud changes

Atmospheric energy loss is now much smaller

Summary

1. New global climate diagnostics for GFS:
- Many fields as good or better than CESM1 climate model
- Cloud rad forcing much too weak, biasing climate warm
- GFS energy leaks compensate this bias

2. GCSS single-column cases test GFS physics
- Shallow Cu entrain too little, precipitate too much

3. Short coupled runs
- Fixing ShCu issues improves global coupled simulation
- Atmos. energy leak fixed by adding dissipative heating.

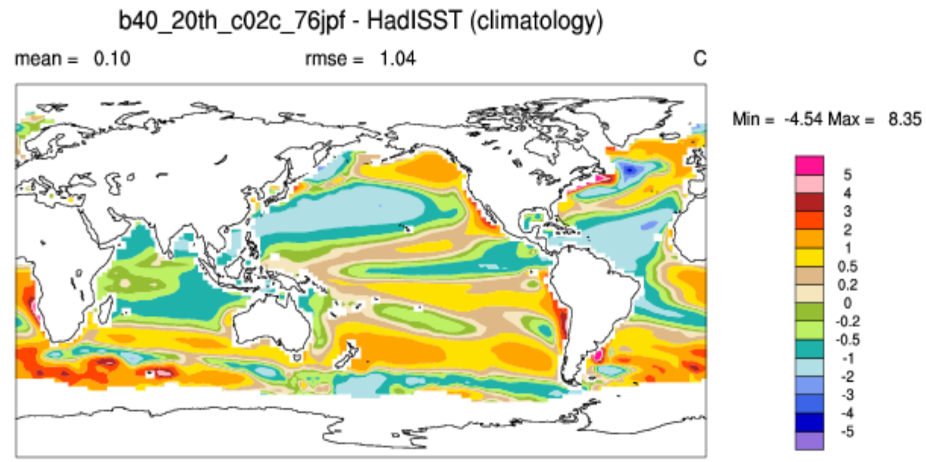
4. EDMF implemented and evaluated in GFS SCM

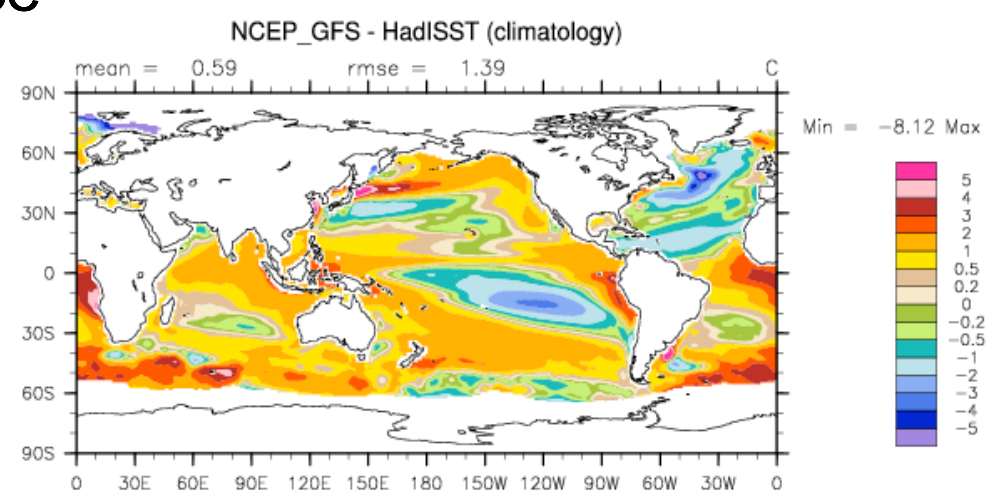
Comparison of NCAR CESM1 and NCEP GFS

Model	NCAR CESM1	NCEP GFS
Atmosphere	CAM5 (2x2.5, L30)	GFS (T126 L64)
Boundary Layer Turbulence	Bretherton-Park (09) UW Moist Turbulence	Han and Pan (11)
Shallow Convection	Park-Bretherton (09) UW Shallow Convection	Han and Pan (11)
Deep Convection	Zhang-McFarlane Neale et al.(08) Richter-Rasch (08)	Han and Pan (11)
Cloud Macrophysics	Park-Bretherton-Rasch (10) UW Cloud Macrophysics	Zhao and Carr (97)
Stratiform Microphysics	Morrison and Gettelman (08) *Double Moment*	Zhao and Carr (97)
Radiation / Optics	RRTMG Iacono et al.(08) / Mitchell (08)	RRTM
Aerosols	Modal Aerosol Model (MAM) Liu & Ghan (2009)	Climatology
Dynamics	Finite Volume	Spectral
Ocean	POP2.2	MOM4
Land	CLM4	NOAH
Sea Ice	CICE	MOM4

NCEP Model Diagnostics (Xiao, Sun, Park)

- NCAR CESM 1.0 (coupled version of CAM 5.0, 200-yr run)
- NCEP GFS (coupled to MOM ocean model, 50-yr)
- NCAR AMWG diagnostic package adapted to GFS output
- Both models skillfully reproduce global circulation patterns.
- GFS avoids double-ITCZ bias.





50 yr C-GFS vs. 100 yr CESM1 climo: AMWG metrics

cor coef: Space-Time	cam3_5_fv1.9x2.5	b40_20th_c02c_76jpf	NCEP_GFS
	ANN	ANN	ANN
Sea Level Pressure (ERA40)	0.949	0.959	0.956
SW Cloud Forcing (CERES2)	0.707	0.714	0.408
LW Cloud Forcing (CERES2)	0.820	0.769	0.781
Land Rainfall (30N-30S, GPCP)	0.785	0.811	0.751
Ocean Rainfall (30N-30S, GPCP)	0.802	0.757	0.733
Land 2-m Temperature (Willmott)	0.876	0.876	0.911
Pacific Surface Stress (5N-5S,ERS)	0.872	0.797	0.834
Zonal Wind (300mb, ERA40)	0.967	0.960	0.957
Relative Humidity (ERA40)	0.900	0.874	0.906
Temperature (ERA40)	0.912	0.932	0.984

C-GFS pattern correlations better than CESM1 for

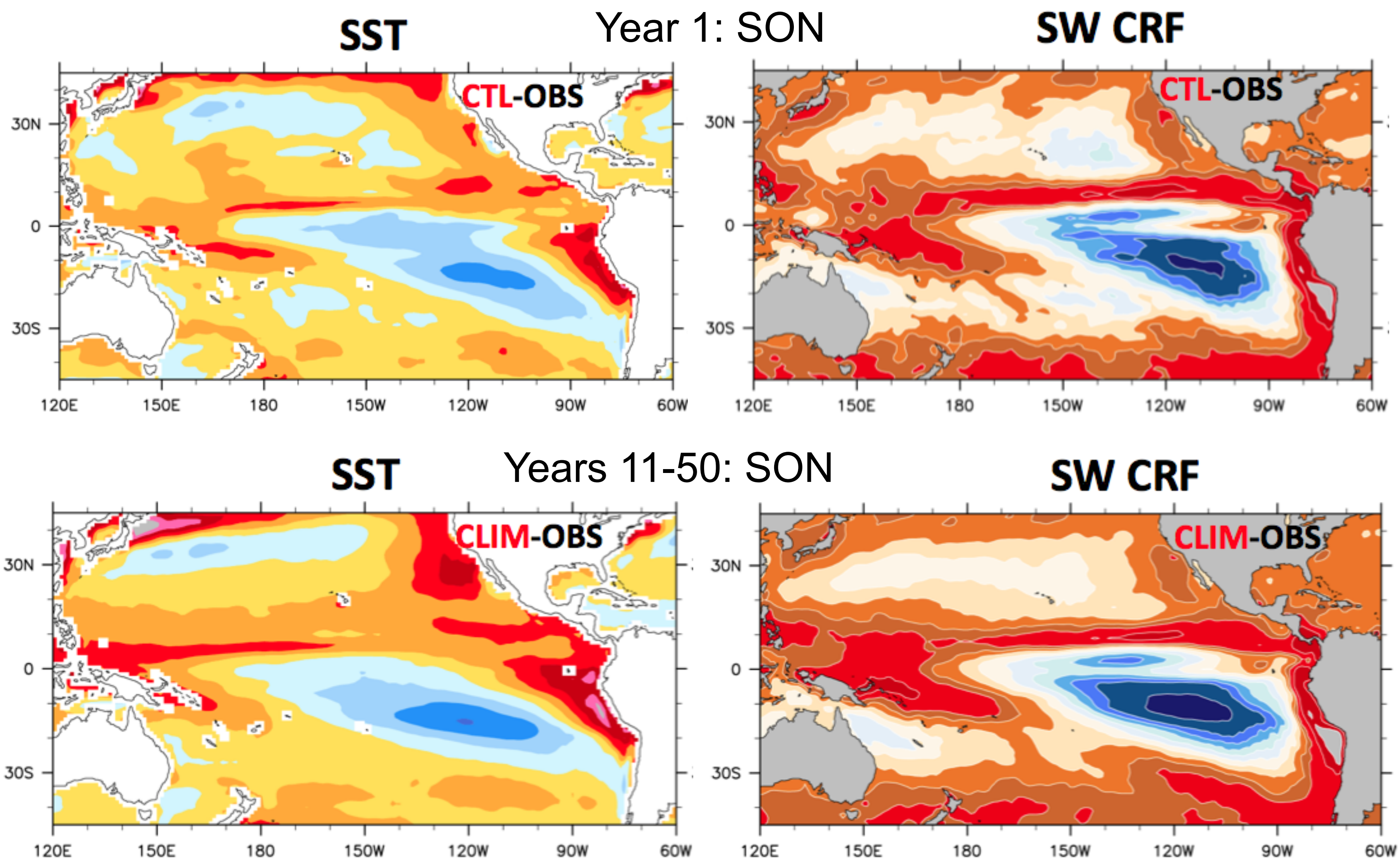
Pac surface stress, land surface temperature, 3D T/RH, but worse for

shortwave cloud forcing, rainfall.

Overall, C-GFS climatology is remarkably good for a weather-tuned model.

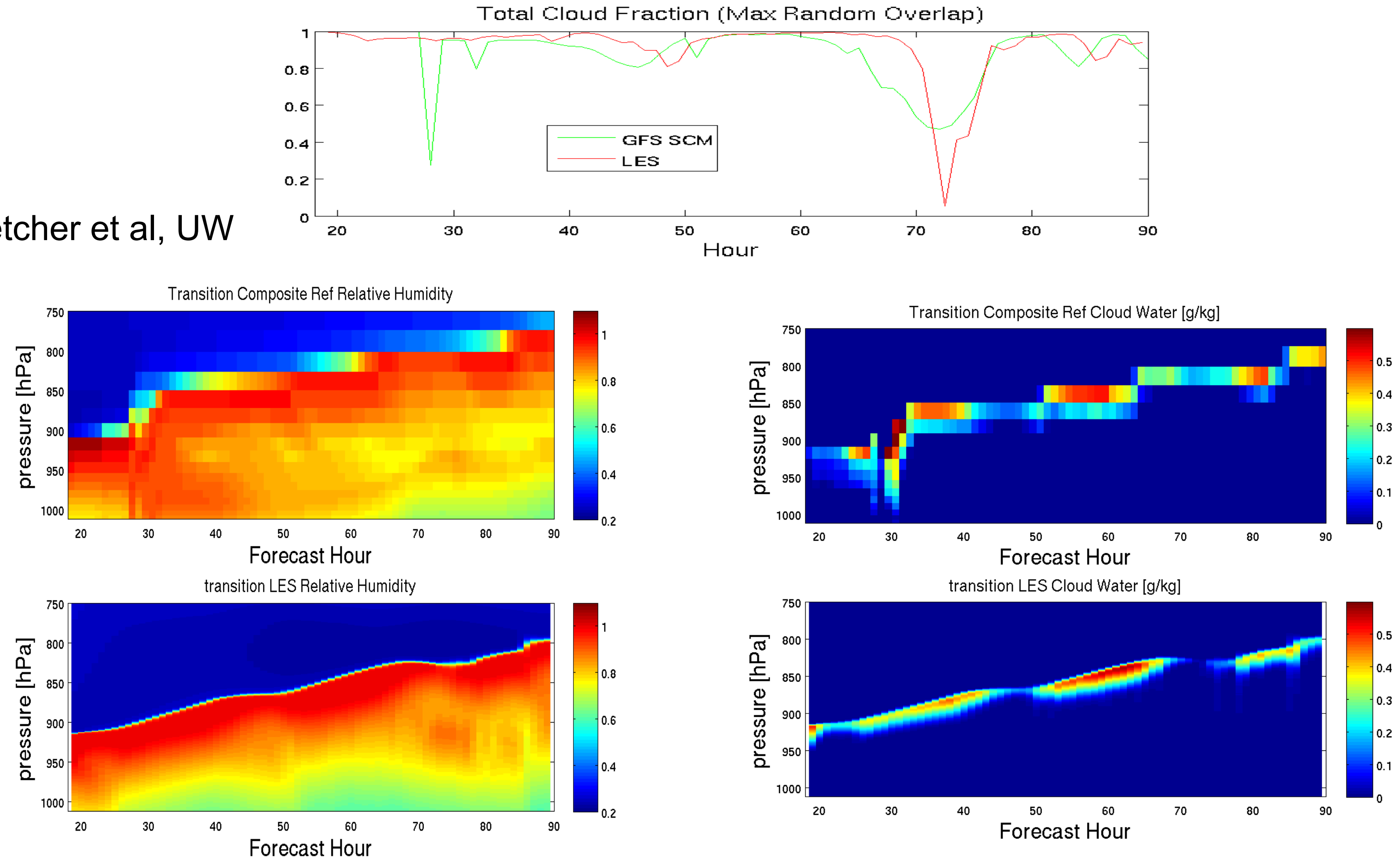
1 year coupled GFS sensitivity runs (Sun, Han, Xiao)

- Tropical cloud/SST biases in coupled model develop fast



Sc-to-Cu composite transition case with NCEP SCM

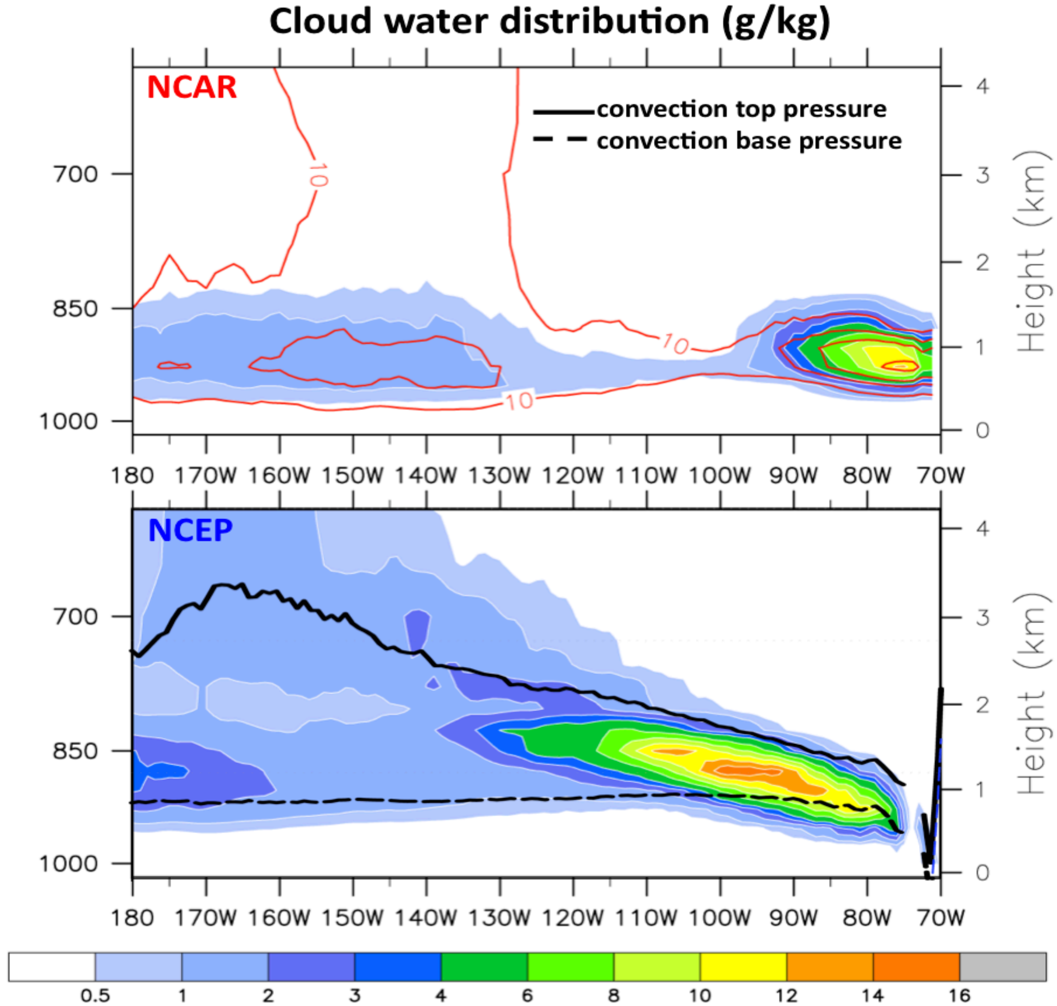
Fletcher et al, UW



GFS SCM results for transition are not too bad

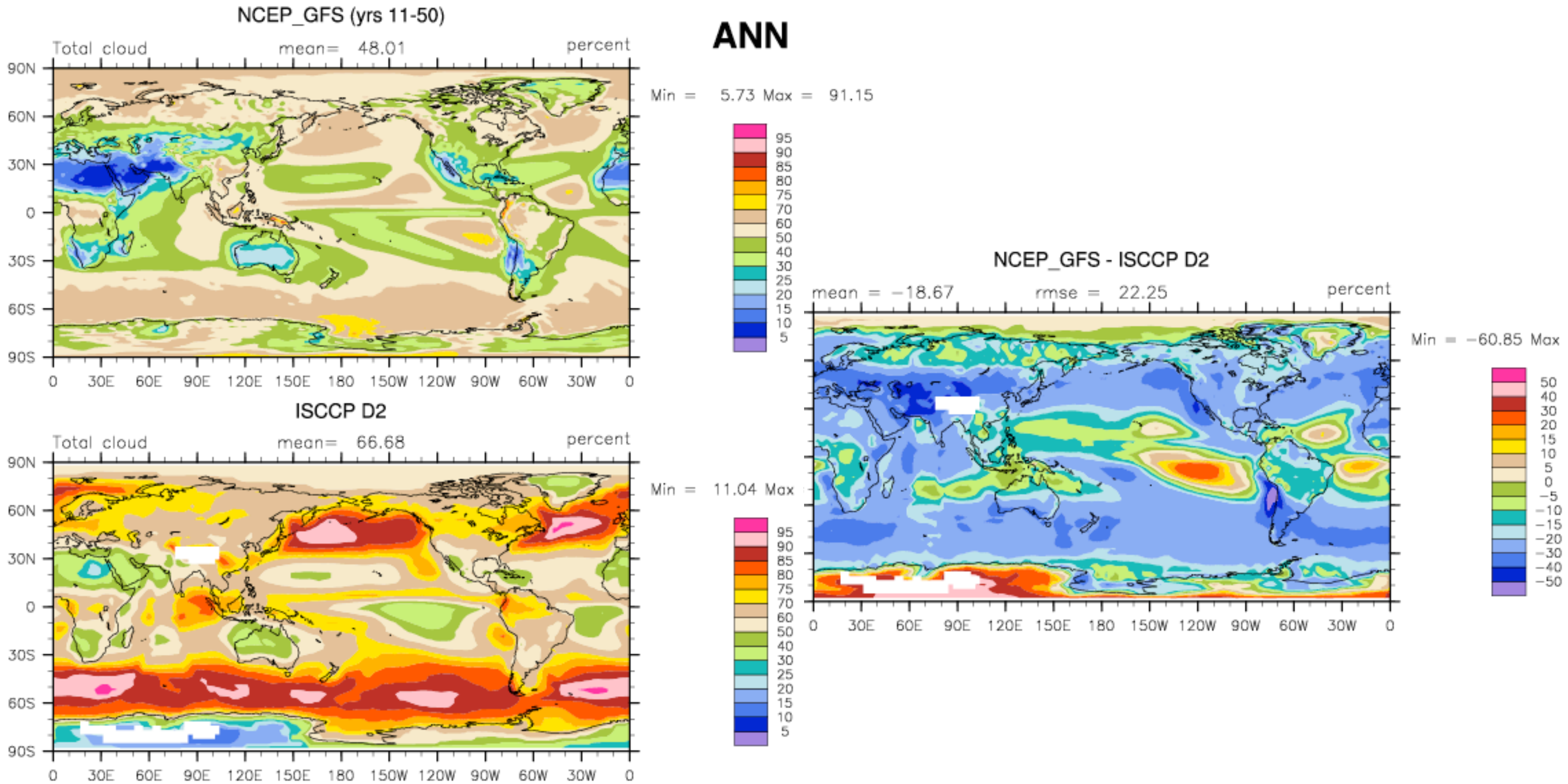
NCEP/NCAR diagnostics of cloud transition

October climatology along 20 S cross-section



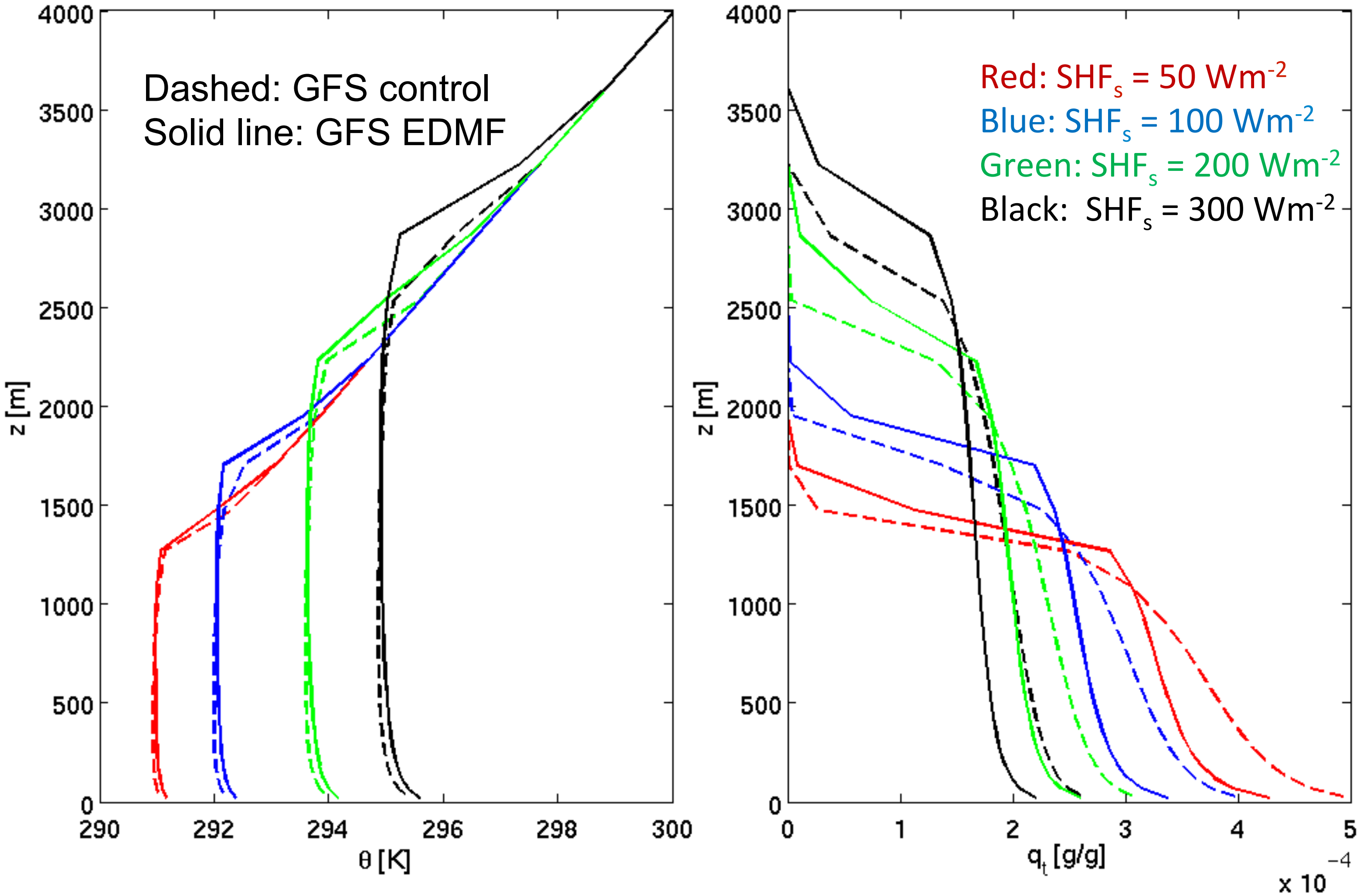
NCAR and NCEP results are significantly different

Main culprit: Too little cloud cover in GFS



Cloud Parameterization? Microphysics? Vertical mixing?

Implementation of EDMF in GFS SCM
Dry convective boundary layer



EDMF improves dry convective boundary layer in GFS

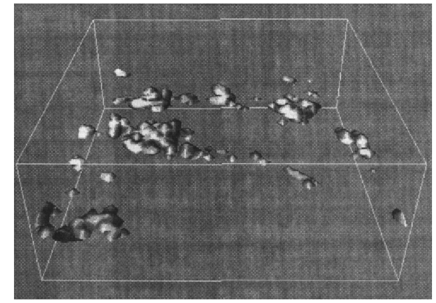
Single-Column Modeling with GFS
(Fletcher et al.)

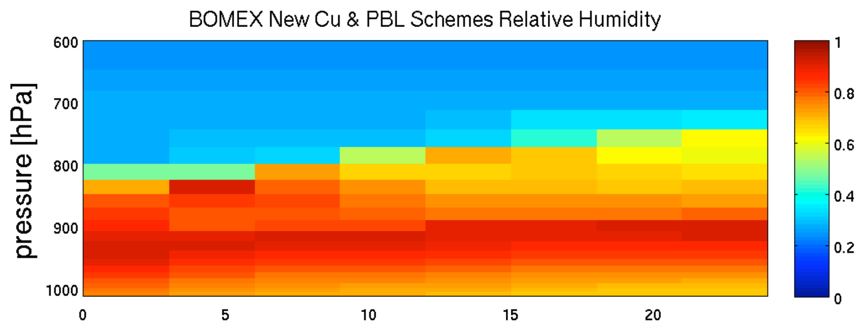
- Single-column GFS existed (pre-2010 physics) but not outside NCEP, nor on intercomparison cases
- Technical issues:
  - Lack of GFS documentation
  - Code inflexible to changes in forcings, physics, outputs
  - Default outputs inadequate to diagnose parameterizations

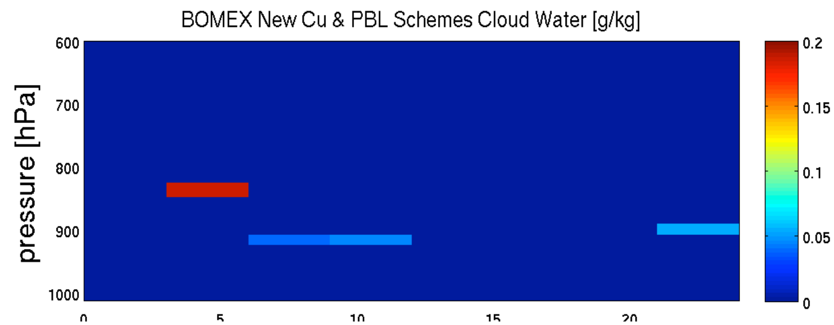
- GFS SCM developed by UW and NCEP with recent physics
- SCM has been adapted to several GCSS cases (Sc, shallow Cu, Sc-Cu transition) for which LES and observations exist
- SCM used at JPL to implement EDMF scheme in GFS

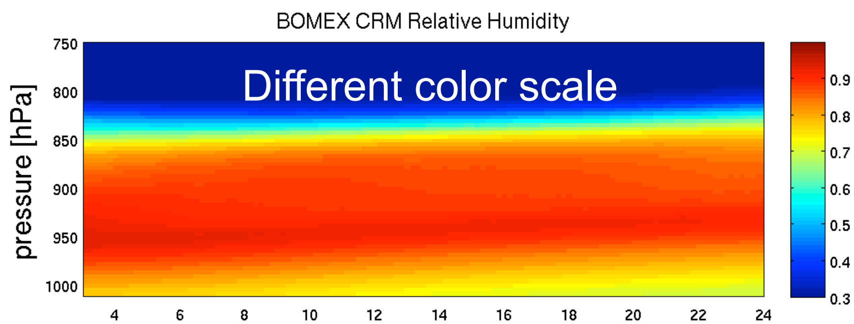
BOMEX nonprecipitating trade Cu case

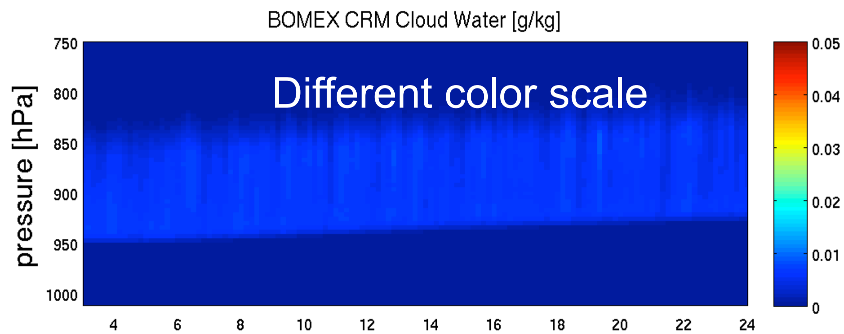
Siebesma et al. 2003



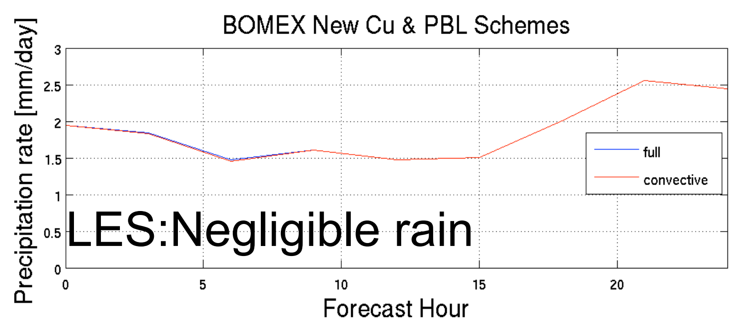








- Too much rain
- Cloud cover problematic
- Physics changes from LES:
  increase lateral entrainment 3x
  decrease precip efficiency 2x



TKE dissipation heating (Han)

$$\varepsilon = \underbrace{-K_h \frac{g}{\theta_v} \frac{d\theta_v}{dz}}_{\text{buoyancy production}} + \underbrace{K_m \left| \frac{d\mathbf{u}}{dz} \right|^2}_{\text{shear production}}$$

4 month coupled GFS runs	TOA (W/m^2)	SFC (W/m^2)	Difference (W/m^2)
CTL	16.2	9.6	6.6
EXP1: same as shortrun2 in Heng (dissipative heating only at the model first layer)	7.9	5.1	2.8
EXP2: same EXP1 but w/o dissipative heating	8.2	2.3	5.9
EXP3: same as EXP1 but w/ dissipative heating over whole atmospheric layer	7.8	6.9	0.9

…atmospheric energy loss is now much smaller